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Subject: Joint operation of Chief Joseph and Grand Coulee Dams for Power and Total Dissolved Gas Production.

Summary

The objective of this investigation was to develop guidance for the joint operation of Grand Coulee Dam and Chief Joseph Dam when spill operations are required. This evaluation investigated the consequences to TDG saturation in the Columbia River of using the outlet works at Grand Coulee Dam with the existing spillway at Chief Joseph Dam. The evaluation of water quality benefits derived from different project operations were based on maintaining a constant joint power output from both projects. Empirical equations were used to estimate the TDG exchange and power production from both projects subject to various river and power output scenarios.

A joint operating policy was developed with the objective of minimizing the average TDG saturation in the Columbia River below Chief Joseph Dam over a wide range of river flows, background TDG levels, and surplus power outputs. The operating policy minimizing the average TDG saturation below Chief Joseph Dam requires avoiding the use of outlet works releases at Grand Coulee Dam by shifting all spill to Chief Joseph Dam for spill discharges up to 70 kcfs. If river conditions require spillway releases above 70 kcfs at Chief Joseph, the additional spill should be distributed between Chief Joseph Dam and Grand Coulee Dam in a 2.5 to 1 ratio. The primary window of usage of the outlet works at Grand Coulee Dam typically occurs from March through early June when forebay pool elevation fall below 1260 ft.

Under this proposed policy, the TDG saturation in Lake Rufus Woods will experience the biggest improvement with reductions in the average TDG saturation as much as 12%. The reduction in the average TDG saturation below Chief Joseph Dam will be small, ranging from 1-3% saturation when compared to typical project operations. The TDG saturation in undiluted spillway releases from Chief Joseph Dam will experience an increase in TDG saturation of up to 7% saturation.

The shift in spill to Chief Joseph Dam will increase the frequency and degree of TDG excursions above the Washington waiver standard of 120% and 125% at the tailwater fixed monitoring station below Chief Joseph Dam. However, this operating policy would also reduce the frequency and degree of TDG excursions at the tailwater FMS below Grand Coulee Dam and at the forebay FMS at Wells Dam.

Introduction

The General Re-evaluation Report, completed in June 2000 for dissolved gas abatement at Chief Joseph Dam (Chief Joseph), recommended installation of flow deflectors at Chief Joseph combined with “Joint Operation” of Chief Joseph with Grand Coulee Dam (Grand Coulee). This combined alternative would provide the greatest benefit of Total Dissolved Gas (TDG) reduction in the Mid-Columbia River. Flow deflectors on Chief Joseph would, by themselves, reduce TDG below the dam during spill conditions. Joint Operation would further reduce TDG above and below Chief Joseph by taking advantage of

- The larger generation flow capacity of Grand Coulee;
- Lower average TDG loading below Chief Joseph during spillway releases, with or without flow deflectors.

If Joint Operation were conducted without flow deflectors, there would be a benefit of reduced TDG in Lake Rufus Woods, the reservoir formed by Chief Joseph. Joint Operation would result in a modest reduction to the average cross sectional TDG saturation in the Columbia River downstream of Chief Joseph, while increasing the local TDG saturation, as measured at the fixed monitoring station (FMS), below the spillway at Chief Joseph. This document further explores the potential water quality benefits associated with Joint Operation of Grand Coulee and Chief Joseph.

Background

Chief Joseph and Grand Coulee have spilled during the spring snowmelt season in almost half of all years. It is estimated that these projects spilled enough to cause TDG saturation greater than 120% in about a quarter of all years. Grand Coulee has the greatest generation flow capacity (280 kcfs) in the Mid-Columbia; Chief Joseph has the second largest at 220 kcfs. Almost all spill at both projects has occurred due to lack of load (surplus generation capacity), rather than due to river flow exceeding their generation capacities. The General Re-evaluation Report determined a design flow with a 10-year return period (7Q10) of 241 kcfs should be used for alternatives evaluation. The 7Q10 can be entirely passed with generation flow and no spill at Grand Coulee. Chief Joseph must spill to pass the 7Q10.

During April 7, 1996 an outlet works spill of about 35 kcfs, less than one-third of the total project flows from Grand Coulee, resulted in an increase in the TDG saturation at the tailwater fixed monitoring station from about 110% to 132%. Outlet works discharges from Grand Coulee were responsible for large increases to the TDG loading of the Columbia River during the 1996 and 1997 spill seasons. A comparable spill of 35 kcfs at Chief Joseph, during powerhouse releases of 140 kcfs on June 9, 1999, caused the average TDG saturation in the Columbia River to rise from 108.7% to 113.2% saturation. These historic events illustrate the difference in the TDG exchange properties between Chief Joseph and Grand Coulee and the potential water quality benefits of considering the joint operation of these projects.

Objective

The objective of this investigation was to develop guidance for the joint operation of Grand Coulee and Chief Joseph when spill operations are required. This joint operation guidance was based on the production of TDG supersaturation in the Columbia River during spill. This evaluation investigated the consequences of using the outlet works at Grand Coulee with the existing spillway at Chief Joseph.

Approach

The need to consider the joint operation of Chief Joseph and Grand Coulee arises when spill is required as a result of excess power generation capacity or when the river flow exceeds the hydraulic capacity of either powerhouse. If spill is a required operation, the question then becomes how to distribute power generation and spill between these projects. The power generation distribution will determine where and how much spill is required and the resultant TDG saturation generated by these operations. When considering alternative operations for a constant joint power output, a 1 kcfs reduction in spill at Grand Coulee must be accompanied by a 1.8 kcfs increase in spill at Chief Joseph. One approach for determining the generation distribution between Chief Joseph and Grand Coulee, involves evaluating the TDG saturation resulting from joint operation. This evaluation requires a means of estimating the power generation from both projects and the TDG exchange associated with project spill. With these project descriptions in hand, the consequences of various joint operation strategies can be investigated over a range of background TDG levels, river flows, and surplus power generation scenarios. The following section provides an overview of the TDG exchange at Chief Joseph and Grand Coulee. These descriptions are followed by a series of evaluations quantifying the TDG saturation resulting from the joint operation of Chief Joseph and Grand Coulee.

TDG Exchange

The evaluation of the TDG exchange at Chief Joseph and Grand Coulee must involve the estimation of the TDG associated with spillway flows, and the average TDG saturation in the Columbia River from both powerhouse and spillway flows. The general equation for the mixed TDG levels in the river produced by various amounts of spill and power flow is given by:

$$TDG_{avg} = \frac{TDG_{spill} * (Q_{spill} + Q_{ent}) + (Q_{ph} - Q_{ent}) * TDG_{ph}}{Q_{total}} \qquad (1)$$

Where TDG_{avg} (%) is equal to the average TDG saturation released from the dam, Q_{spill} (kcfs) is the rated spillway release (outlet works or spillway release), Q_{ph} (kcfs) is the rated powerhouse release, Q_{ent} (kcfs) is the powerhouse discharge entrained into the aerated spillway release and thereby subjected to accelerated TDG exchange, TDG_{spill} (%) is the TDG saturation associated with the effective spillway discharge (Q_{spill}+Q_{ent}), and TDG_{ph} is the TDG saturation of powerhouse releases. The fate of powerhouse releases can be explored in this formulation where a portion of the powerhouse discharge Q_{ent} is entrained into the aerated spillway jet and exposed to the accelerated exchange of atmospheric gases. The residual powerhouse discharge (Q_{ph}-Q_{ent}) will be available to dilute the TDG flux associated with the effective spillway discharge.

Grand Coulee TDG Characteristics. The TDG exchange characteristics of Grand Coulee are complicated by the type and operating variability of the outlet works, spillway, stilling basin design, tailrace channel features, forebay water quality properties, and powerhouse configuration and operation. The three distinct modes of release involve powerhouse discharge, outlet works discharge, and spillway releases over the drum gates.

Grand Coulee must pass non-powerhouse releases through outlet works, a series of 40 conduits with outlets located on the spillway face at elevations 1050 and 1150 when the forebay elevation is less than 1260 ft. Under normal reservoir operations, each outlet tube is capable of discharging from 3 to 5 kcfs, depending upon the outlet elevation and the lake level. When Grand Coulee spills through the outlet works, high TDG saturations are generated as observed during a field study conducted by the BOR (Frizell, 1997). The TDG saturation as high as 147.2 % was observed 2.3 miles downstream from the dam during an outlet works release of 33.7 kcfs. There was some evidence to suggest that the paired upper and lower operation of outlet works can reduce the exchange of TDG during outlet works discharges.

A limited study of TDG exchange properties at Grand Coulee was conducted in March 1997 (Frizell, 1997). The information gathered during this study was used in conjunction with TDG data collected at the fixed monitoring stations (FMS) to develop a TDG exchange formulation for outlet works flows from Grand Coulee as described in (Schneider, 1999). The recommended description of TDG exchange assumes outlet works releases will be gassed up to 146% regardless of the location or sequence of outlets tubes. In order to reproduce the TDG loading inferred in the downstream FMS data, an entrainment discharge was required equaling 1.56 times the outlet works discharge. The entrainment discharge refers to the amount of powerhouse flow entrained into the aerated outlet works release. It was assumed that powerhouse waters entrained into the aerated outlet works flows would also attain a TDG saturation of 146%. The powerhouse flows not entrained into the outlet works discharge were assumed to contain the TDG saturation observed in the forebay. This exchange relationship for outlet works flows at Grand Coulee greatly simplifies the complex processes contributing to TDG exchange at this project. The inclusion of an entrainment component, although physically plausible given the attributes of the project, is not based on direct observations. This simple exchange formulation was developed from observations in 1997 and provided a standard error of 1.31% (Schneider, 1999). The delta pressure or excess pressure above atmospheric pressure of outlet works flows was defined by the following relationship.

$$\Delta P = 340.0 \qquad (2)$$

$$Q_{ent} = 1.56\ Q_{sp}$$

$R^2 = 0.88$
Standard Error = 9.7 mm Hg

Where:

ΔP = Excess TDG Pressure above Barometric Pressure (mm Hg)
Q_{sp} = total spillway discharge (kcfs)
Q_{ent} = Entrainment of powerhouse discharges into aerated spill (kcfs)
TDG = $100*(BP+\Delta P)/BP$ Total Dissolved Gas Saturation (%)
BP = Barometric Pressure (mm Hg)

Flow can be passed over the spillway at Grand Coulee as regulated by 11 drum gates, when the forebay elevation exceeds elevation 1260 ft. The drum gate releases widely distribute water across the entire width of the spillway greatly reducing the unit discharge, momentum, and plunge of the spillway jet into the stilling basin. *The TDG exchange associated with drum gate spillage at Grand Coulee is not well defined and great care should be exercised in applying equation 3 estimating TDG exchange during this type of operation.* The TDG level associated with drum gate releases was found to be an exponential function of the total spillway discharge with zero entrainment discharge. The excess pressure above atmospheric pressure of spillway flows was defined by the following relationship.

$$\Delta P = 451\ (1 - e^{-0.0298 Q_{sp}}) \qquad (3)$$

$$Q_{ent} = 0.0$$

R^2=0.97
Standard Error = 6.5 mm Hg

Chief Joseph Dam TDG Characteristics.

A comprehensive study of the TDG exchange properties at Chief Joseph was conducted during June 6-11, 1999 with the finding presented in (Schneider, 1999b). An array of 28 automated water quality sondes capable of measuring the TDG pressure were deployed above and below Chief Joseph. A series of spillway releases were scheduled to study the effects of both spill pattern and total spill discharge on the TDG exchange at Chief Joseph. The spill discharge ranged from 16.0 to 96.5 kcfs. The following conclusions were drawn from a review of velocity and TDG data taken during this study.

- The average TDG production from standard spillway releases at Chief Joseph Dam was found to be an exponential function of the unit spillway discharge. The TDG saturation ranged from 111 percent for a unit spillway discharge of 1 kcfs/bay to 134 percent for spillway discharges of 5 kcfs/bay and larger.

- The TDG saturation as measured at the tailwater FMS was representative of spillway releases.

- The TDG pressures of powerhouse releases were nearly identical to TDG pressures measured in the forebay. The powerhouse releases simply pass on TDG conditions created at upstream dams.

- The entrainment of powerhouse releases into the aerated plume of spillway discharges appears to be quite small and does not significantly influence the TDG produced during project operation.

The TDG exchange relationship developed during this study was further enhanced to account for the dependency between stilling basin depth of flow on total river flow. The following equation for delta pressure describes the resultant TDG exchange at Chief Joseph under current project conditions with no entrainment of powerhouse release into the aerated spill.

$$\Delta P = (TWE - 743)(6.104 - 5.08e^{-0.48qs}) \qquad (4)$$

$$Q_{ent} = 0.0$$

$$R^2 = 0.88$$

Standard error = 17.5 mm Hg

Where: ΔP = TDG pressure minus barometric pressure (mm Hg)
TWE = Tailwater elevation in feet.
q_s = Specific Spill Discharge (kcfs/bay)
TDG = 100*(BP+ΔP)/BP Total Dissolved Gas Saturation (%)
BP = Barometric Pressure (mm Hg)

Relative Comparison of TDG Exchange

The relative difference in TDG exchange from outlet works spill at Grand Coulee and Chief Joseph can be demonstrated from the following scenario for 200 kcfs total river flow in the Columbia River and a background TDG saturation of 120% in Lake Roosevelt. The discharge of 25, 50, and 75 kcfs through the outlets tubes at Grand Coulee will result in a 4.3, 16.7, and 25.1% saturation increase in Lake Rufus Woods. The discharge of 25, 50, and 75 kcfs spill at Chief Joseph will result in a 0.1, 2.1, and 4.6% saturation increase in the average TDG saturation in Lake Pateros. Based on this simple analysis, the outlet works releases from Grand Coulee will produce an increase in TDG saturation of up to 8 times the estimated increase associated with the same operating event at Chief Joseph.

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These and forthcoming estimates of TDG saturation in the Columbia River assume the following:

- no loss of TDG saturation during transport through Lake Rufus Woods,
- sustained operations allowing steady conditions to develop throughout Lake Rufus Woods and Lake Pateros,
- spill discharge through the outlet works at Grand Coulee and over the spillway at Chief Joseph
- the TDG production relationships presented in Equations 1-4 apply for a wide range of operating conditions at these projects.

It is helpful to review the joint operation alternatives at Chief Joseph and Grand Coulee when spill is required because of a surplus power generation capacity from these projects. The spectrum of joint operations of Chief Joseph and Grand Coulee were determined for conditions requiring a power output of 6289 MWhrs, a surplus power capacity of 262 MWhrs, for a total river flow of 200 kcfs and a TDG saturation of 115% in Lake Roosevelt. The forebay elevation in Lake Roosevelt and Lake Rufus Woods were assumed to equal 1256 ft and 953.9 ft, respectively for this evaluation. The range of possible joint operations involve spilling only at Chief Joseph, concurrent spill at both projects in varying ratios, and spill only through the outlet works at Grand Coulee. These alternative flow conditions and the resultant average TDG saturation in the Columbia River are listed in Table 1 and shown in Figure 1.

Event 1 assumes no spill at Grand Coulee and about 22 kcfs spill from Chief Joseph. This operation results in the average TDG saturation in Lake Rufus Woods of 115% equal to conditions in Lake Roosevelt. The TDG saturation in spill water undiluted from powerhouse releases at Chief Joseph was estimated to be about 119.5% resulting in an average TDG saturation in the Columbia River below Chief Joseph (Lake Pateros) of 115.5%, an increase of about 0.5% above forebay conditions. At the other end of the spectrum is Event 21, where no spill at Chief Joseph would force an outlet works flow of about 12.4 kcfs at Grand Coulee resulting in the average TDG saturation in Lake Rufus Woods and Lake Pateros of 120%, a 5% increase over background conditions in Lake Roosevelt.

Events 2 through 20 represent concurrent spill from both projects progressing from a high ratio of spill at Chief Joseph to Grand Coulee, to a low spill ratio. The consequences to Columbia River TDG levels of shifting spill away from Chief Joseph to the outlet works at Grand Coulee is for increasing average TDG conditions in the Columbia River (115%-120%) while lowering the TDG saturation in undiluted spill from Chief Joseph from 119.5% to 106%. For these river conditions, the joint operation of only spilling from Chief Joseph will result in the lowest average TDG saturation in the Columbia River at the expense of elevated TDG saturation in undiluted spillway releases from Chief Joseph. This evaluation was for a set of specific conditions involving river flow, Lake Roosevelt TDG levels, and surplus power output. The determination of a joint operating policy requires the examination of a much broader range of river conditions and power surplus alternatives.

Spill Management

Inconsistencies in the management of spill can arise when treating the TDG information from tailwater FMS of these two projects as comparable measures of river conditions. The FMS located about 6 miles below Grand Coulee measures a mixed river (Frisell, 1997), the result of a fully developed mixing zone composed of both generation flow and spill. In contrast, the FMS below Chief Joseph located about 1.25 miles below the dam on the spillway side of the river, measures only the TDG pressure associated with project spill. This sampling station is not an indicator of average river conditions because it is not influenced by the dilution of releases from the powerhouse. Unlike Grand Coulee, generation flow and spill below Chief Joseph do not completely mix until the water is about halfway to Wells Dam, a distance of 10 miles.

The spill management plan calls for applying incremental levels of spill at each project for the purpose of maintaining quasi-uniform TDG condition throughout the Columbia River basin. The information at the tailwater FMS are used as indicators when these incremental levels of spill are to be applied. This management policy may generate unexpected consequences for TDG levels below Grand Coulee and Chief Joseph because of the different types of measures maintained at the tailwater FMS's below these projects. As an example, the 2002 spill management plan recommends a spill discharge of 33 kcfs at Chief Joseph and 20 kcfs spill through the outlet works at Grand Coulee when river conditions reach 125% saturation. The TDG expected below Grand Coulee and Chief Joseph for 200 kcfs river flow and 125% background condition in Lake Roosevelt were estimated assuming the recommended spill operations laid out in the spill management plan as shown in Case 1 in Table 2. The outlet works flow of 20 kcfs at Grand Coulee increases the TDG saturation in Lake Rufus Woods by 5.4 percent to 130.4%, while a spill of 33 kcfs at Chief Joseph degasses the river lowering the average TDG saturation to 129.3% as shown in Case 1 (CHJ) in Table 2. The net effect of this spill strategy does maintain nearly uniform TDG conditions through this river reach. However, Grand Coulee was responsible for the entire uptake, and spill at Chief Joseph contributed to reducing the TDG conditions in the river.

An alternative spill policy was investigated to achieve a reduction in the average TDG saturation below Chief Joseph while maintaining a constant joint power generation output. For the same river flow (200 kcfs) and background TDG conditions (125%) in Lake Roosevelt, the policy of only spilling water at Chief Joseph would have lowered the average TDG saturation in Lake Rufus Woods from 130.4% (Table 2, Case 1 GCL) to 125% (Table 2, Case 2 GCL), and below Chief Joseph from 129.3% (Table 2, Case 1 CHJ) to 127.2% (Table 2, Case 2 CHJ). Again, this modest reduction in average TDG saturation below Chief Joseph was accomplished by eliminating outlet works releases from Grand Coulee and increasing spill and the local TDG saturation in spill water below Chief Joseph from 123.7% (Table 2, Case 1 CHJ) to 131.4% (Table 2, Case 2 CHJ).

Optimal Joint Operating Policy

It was the objective of this study to formulate an operational policy that would reduce TDG conditions in the reach of the Columbia River from Grand Coulee to below Chief Joseph while maintaining the joint power production capacity. The water quality target chosen for development of an operational policy was to minimize the average TDG saturation below Chief Joseph. This policy would contain the influence of spilling water at both projects since upstream TDG conditions are passed downstream of Chief Joseph during hydropower releases. The level of spill at Chief Joseph would further alter the TDG composition in the Columbia River in Lake Pateros. There are many other TDG objective functions that could be formulated to evaluate the joint operation of these two projects. The selection of a different TDG objective statement may lead to a different operational policy.

A means of measuring the impacts afforded by the recommended operational policy is also required to aid in the formulation of spill management policy. A base condition or typical operating framework was required to compare changes in TDG properties against the optimal operating conditions. The location and degree of change in TDG conditions in the Columbia River as determined from the comparison of two operational policies, can then be factored into the final spill management decision. The base condition was assumed to consist of a spill management policy where spill at Chief Joseph was twice the rate of outlet works spill at Grand Coulee. This two-to-one ratio was determined from average conditions observed during the high flow spill season in 1997.

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The power production and total dissolved gas saturation associated with Chief Joseph and Grand Coulee were considered components of a resource allocation problem. The general objective of this problem involves attaining water quality objectives while meeting a joint power generation demand. The optimal operation of each project will be dependent upon the water quality goal, the flow rate in the system, power generation demand, and background total dissolved gas saturation present in Lake Roosevelt. An infinite number of joint operating conditions can be scheduled if the surplus power generation quantity is known, but only one set of operating conditions will result in conditions most closely achieving TDG saturation objectives. A set of empirical equations was used to estimate the amount of power generated from a given set of operations as a function of the powerhouse discharge and project head. The TDG saturation properties were also based on a set of empirical production equations described above in Equations 1-4. The following study results only consider the operations associated with outlet works releases at Grand Coulee and exclude spillway releases controlled by the drum gates.

A procedure to search for the joint operating condition, which would generate a specified power output while minimizing the water quality impacts, was devised. An Excel spreadsheet (JointOps.xls) was developed which contains estimates of power and TDG production as a function of project operations. This spreadsheet evaluates the joint operation of Grand Coulee and Chief Joseph based on power generation and water quality objectives. The total river flow and spill discharge are required inputs, with the powerhouse flow calculated from these conditions. The spill discharge and tailwater elevation are used to estimate the resultant TDG saturation in spill water. The powerhouse discharge is assumed to contain forebay TDG levels at each project. The flow-weighted TDG saturation in the Columbia River can then be calculated first below Grand Coulee and then at Chief Joseph.

The distribution of power and spill flow can be entered manually or determined through one of three optimization strategies. The optimization strategies will determine the spill discharge at each project yielding a specified power generation target, but limited by a set of flow and water quality constraints. For the purpose of this study, the base condition optimization pursues a management strategy of spilling from both projects at a fixed ratio. The case 1 optimization pursues a management strategy of spilling water from both projects in any ratio to minimize the average TDG below Chief Joseph. The case 2 optimization pursues a management strategy of spilling water to generate a uniform TDG below both Chief Joseph and Grand Coulee. The add-in module to the Microsoft Excel spreadsheet called “Solver” was used to compute the optimal operation that minimizes the average TDG saturation below Chief Joseph while attaining a specified power output. This non-linear optimization solution generally finds the globally optimal solution. In a limited number of cases, the problem statement is over-defined and a globally optimal solution is not found. The optimization problems solved by this spreadsheet are listed below.

Optimization Base Condition $$Min\ \ TDG_{avg}^{CHJ}(Q_{sp}^{CHJ}, Q_{sp}^{GCL}) \qquad (5)$$

Subject to:
$$MW_{CHJ} + MW_{GCL} = MW_{Target}$$
$$Q_{ph}^{\min} < Q_{ph}^{CHJ} < Q_{ph}^{\max}$$
$$Q_{ph}^{\min} < Q_{ph}^{GCL} < Q_{ph}^{\max}$$
$$\frac{Q_{sp}^{GCL}}{Q_{sp}^{CHJ}} = c_1$$

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Optimization Case 1 $$Min\ \ TDG_{avg}^{CHJ}(Q_{sp}^{CHJ}, Q_{sp}^{GCL}) \qquad (6)$$

Subject to:
$$MW_{CHJ} + MW_{GCL} = MW_{Target}$$
$$Q_{ph}^{\min} < Q_{ph}^{CHJ} < Q_{ph}^{\max}$$
$$Q_{ph}^{\min} < Q_{ph}^{GCL} < Q_{ph}^{\max}$$

Optimization Case 2 $$Min\ \ TDG_{avg}^{CHJ}(Q_{sp}^{CHJ}, Q_{sp}^{GCL}) \qquad (7)$$

Subject to
$$MW_{CHJ} + MW_{GCL} = MW_{Target}$$
$$Q_{ph}^{\min} < Q_{ph}^{CHJ} < Q_{ph}^{\max}$$
$$Q_{ph}^{\min} < Q_{ph}^{GCL} < Q_{ph}^{\max}$$
$$TDG_{avg}^{CHJ} = TDG_{avg}^{GCL}$$

<u>Results – Joint Operation Strategy</u>

The joint operation of Grand Coulee and Chief Joseph was determined through the application of a spreadsheet determining the optimal distribution of both spill and power generation. For the purpose of this study, the spill distribution was determined to minimize the average TDG saturation below Chief Joseph subject to attaining a target power output (Case 1). The objective statement and constraints used to calculate the spill and power distribution are listed in Equation 6.

The resultant power production and TDG saturation were determined for a range of river conditions. The optimal spill management strategy involved minimizing the average TDG saturation below Chief Joseph while maintaining a target power generation requirement and with the project operations constrained plant capacity. The scenarios developed were based on the following parameters. The forebay elevation for Wells, Chief Joseph, and Grand Coulee Dams were 779, 953.9, and 1256 ft, respectively. The spillage of water at Grand Coulee was limited to the outlet works for this investigation. The barometric pressures used in all the calculations were 739, and 737 mm Hg respectively for Chief Joseph and Grand Coulee. The maximum hydraulic capacity used for the Chief Joseph and Grand Coulee powerhouses were 220 and 250 kcfs, respectively. These values represent conditions that have historically been observed at Wells Dam, Chief Joseph, and Grand Coulee.

The solution to the resource allocation problem depends upon the value of three critical parameters: 1) the total river flow, 2) the power demand, and 3) background TDG saturation in Lake Roosevelt. Wide ranges of system conditions were evaluated by varying these key input parameters over a broad range of conditions. The total river flow was assumed to range from 150 to 260 kcfs in 10 kcfs increments. The upper end of this discharge range required forced spill from Chief Joseph and Grand

Coulee. The marketable power demand is required to estimate the excess water that will pass through either the outlet works at Grand Coulee or the spillway at Chief Joseph. The power generation ratio (PGR) was defined as the marketable power generation divided by the capacity power generation. For instance, a power demand coefficient of 0.8 assumes that the marketable power demanded from the combined plants was 80 percent of the joint power generation capacity as limited by the total river flow or available plant capacity. The power demand coefficient ranged from 0.60 to 1.0 for this analysis. The forebay total dissolved gas saturation in Lake Roosevelt was varied from 105 to 130% and reflects conditions that have historically been observed above Grand Coulee.

A broad range of system conditions (1512 scenarios) were considered in determining the optimal operating conditions. The project operations, TDG levels, and power output summary for a constant PGR of 0.90 are shown in Table 3. This small subset of outcomes shows the amount of spill required will increases as a function of total river flow for a constant PGR. Based on the input parameters outlined above, the optimization program recommended shifting all of the spill away from Grand Coulee xcept during forced spill conditions independent from the initial TDG saturation in Lake Roosevelt.

A review of all of the results from this analysis was conducted and some general observations noted. The TDG saturation in Lake Roosevelt did not influence the optimal operations resulting in the minimum average TDG below Chief Joseph for surplus power output less than 800 MW-hrs. However, the TDG saturation in Lake Roosevelt will influence the magnitude of TDG levels obtained in the river. For surplus power output greater than 800 WMhrs, the TDG saturation in Lake Roosevelt exhibited a small influence on the optimal project operations. The higher the TDG saturation in Lake Roosevelt, the smaller the potential reduction in average TDG saturation below Chief Joseph that can be achieved by spill flow redistribution measures when compared to the base condition (fixed spill ratio).

The optimal operating policy for joint operation of Chief Joseph and Grand Coulee called for all of the spill through the outworks at Grand Coulee to be shifted to Chief Joseph up to a spillway discharge or about 70 kcfs. If conditions require spillway releases above 70 kcfs at Chief Joseph, the additional spill should be distributed between Chief Joseph and Grand Coulee in a 2.5 to 1 ratio. For example, the progression of the paired spill distribution between Chief Joseph and Grand Coulee (Q_{sp} CHJ, Q_{sp} GCL) for increasing levels of surplus generation capacity would be (50, 0), (60, 0), (70, 0), (80, 4), (90, 8), and (100, 12) and so forth, as shown in Table 4. More detailed guidance regarding optimal joint operating conditions can be generated from specific conditions involving the TDG saturation in Lake Roosevelt and current lake levels.

The optimal spill discharges for both Chief Joseph and Grand Coulee were plotted against the surplus power output as shown in Figure 2, excluding forced spill conditions (Q_{total}<220 kcfs). These data indicate that the optimal operating policy was independent of the total river flow and background TDG levels for Chief Joseph spill up to 70 kcfs. The optimal spill discharges exhibit an increasing variance as the surplus power output increased above 800 MWhrs indicating a small dependency on background TDG saturation. The lower the background TDG saturation in Lake Roosevelt, the larger the spill contribution from Grand Coulee.

The change in TDG levels throughout the study area afforded by the optimal spill policy was compared to base conditions consisting of a fixed 2 to 1 spill ratio (Q_{sp}-CHJ to Q_{sp}-GCL). The differences in TDG saturation for the same river conditions (power output, total river flow, Lake Roosevelt TDG saturation) were plotted as a function of surplus power output. The optimal operating conditions (Case 1) were subtracted from the base conditions as shown in Figure 3. This figure shows the greatest improvement in TDG saturation will be located throughout Lake Rufus Woods. The improvement in average TDG conditions below Grand Coulee will be indirectly related to Lake Roosevelt TDG saturation. The improvement in TDG saturation will increase in proportion to the amount of spill shifted from Grand Coulee to Chief Joseph. The reduction in average TDG saturation generally ranged from 5 to 10 percent saturation in Lake Rufus Woods.

The reduction in the average TDG saturations in the Columbia River below Chief Joseph will generally range from 1 to 3 percent saturation. The greatest improvements will be realized during operations spilling only at Chief Joseph. The level of improvement below Chief Joseph can be greater than indicated when the ratio of Grand Coulee spill to Chief Joseph spill is greater than 0.5. The degree of TDG reduction below Chief Joseph was similar to conditions summarized in the General Reevaluation Report (USACE, 2000).

The redistribution of spill to Chief Joseph will increase TDG saturation in undiluted spillway releases at Chief Joseph. The higher spill rates will generate higher TDG pressures and impact a larger volume of the Columbia River immediately below the dam. The TDG saturation in spillway releases from Chief Joseph was estimated to increase by up to 7 %, as shown in Figure 3. The TDG saturation in spill at Chief Joseph will exceed 130 % for a spill discharge of 70 kcfs with comparable levels measured at the tailwater FMS. The TDG saturation in spillway releases is independent from background TDG levels.

The sensitivity of the optimal operating conditions to the uncertainty in estimating the TDG exchange associated with outlet works spill at Grand Coulee was also investigated. The TDG loading associated with outlet works releases at Grand Coulee was reduced by 25% by changing the entrainment coefficient from 1.56 to 0.92. The optimal operating conditions using the Case 1 optimization statements were determined for the same range in system conditions. The optimal operating conditions for these conditions are shown in Figure 4. The management strategy identified from the reduced Grand Coulee TDG loading assumption would be to shift all outlet works spill to Chief Joseph for spill up to 50 kcfs. Additional spill would be derived from a policy distributing spill between Chief Joseph to Grand Coulee at a 2 to 1 ratio, respectively.

Conclusions

The joint operation of Chief Joseph and Grand Coulee can be devised to meet power generation demands while minimizing the average TDG saturation below Chief Joseph when spill operations are required. The amount and location of spill will be influenced by the magnitude of surplus generation capacity, the hydraulic capacity of each powerhouse, and the background TDG saturation in Lake Roosevelt. The operating policy minimizing the average TDG saturation in the Columbia River below Chief Joseph Dam requires avoiding the use of outlet works releases at Grand Coulee Dam by shifting all spill to Chief Joseph Dam for spill discharges up to 70 kcfs. If river conditions require spillway releases above 70 kcfs at Chief Joseph, the additional spill should be distributed between Chief Joseph and Grand Coulee Dams in a 2.5 to 1 ratio.

The TDG saturation in Lake Rufus Woods will experience the biggest improvement under this policy with reductions in the average TDG saturation as high as 12%. The reduction in the average TDG saturation in the Columbia River below Chief Joseph will be small (1-3%) when compared to typical historic operations. The TDG saturation in undiluted spillway releases from Chief Joseph will experience an increase in TDG saturation of up to 7% saturation. Consequently, the shift in spill to Chief Joseph will increase the frequency and degree of TDG excursions above the State of Washington waiver standard of 120% and 125% at the tailwater FMS below Chief Joseph even though the average TDG in the Columbia River below Chief Joseph will be reduced. This operating policy will also reduce the frequency and degree of TDG excursions above the State of Washington standards at the tailwater FMS below Grand Coulee and at the forebay FMS at Wells Dam.

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The determination of an effective joint spill policy will depend upon an understanding of TDG exchange at both Chief Joseph Dam and Grand Coulee Dam and the subsequent exchange, transport, and mixing throughout Lake Rufus Woods and Lake Pateros. The uncertainties associated with estimates of TDG exchange from Grand Coulee Dam need to be factored into the interpretation of these study results and recommendations. A better understanding of the TDG exchange processes at Grand Coulee Dam would enable a more effective joint management of spill from Chief Joseph Dam and Grand Coulee Dam.

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Table 1. Joint Project Operations and TDG Saturation at Grand Coulee (GCL) and Chief Joseph (CHJ) Dams for a Constant Power Output of 6289 MW_{hrs}.
(Power Generation Ratio = 0.96, Total River Flow=200 kcfs, Lake Roosevelt TDG=115%)

Input Parameters			Operations (kcfs)						TDG Saturation (%)						Power Production (MWhrs)					
			GCL			CHJ			GCL			CHJ			GCL		CHJ		Joint	
Event	TDG_{fb} GCL[1]	PGR[2]	Q_{total}[3]	Q_{ph}[4]	Q_{sp}[5]	Q_{total}	Q_{ph}	Q_{sp}	TDG_{ph}[6]	TDG_{sp}[7]	TDG_{avg}[8]	TDG_{ph}	TDG_{sp}	TDG_{avg}	MW_{max}[9]	MW[10]	MW_{max}	MW	MW_{Cap}	MW
1	115	0.96	200.0	200.0	0.0	200.0	177.6	22.4	115.0	146.1	115.0	115.0	119.6	115.5	4206.4	4206.4	2344.6	2082.6	6551.1	6289.0
2	115	0.96	200.0	198.1	1.9	200.0	181.1	18.9	115.0	146.1	115.8	115.8	118.0	116.0	4206.4	4166.4	2344.6	2122.6	6551.1	6289.0
3	115	0.96	200.0	196.7	3.3	200.0	183.6	16.4	115.0	146.1	116.3	116.3	116.8	116.4	4206.4	4137.1	2344.6	2151.9	6551.1	6289.0
4	115	0.96	200.0	195.6	4.4	200.0	185.5	14.5	115.0	146.1	116.7	116.7	115.8	116.7	4206.4	4114.6	2344.6	2174.4	6551.1	6289.0
5	115	0.96	200.0	194.8	5.2	200.0	187.0	13.0	115.0	146.1	117.1	117.1	114.9	116.9	4206.4	4096.8	2344.6	2192.2	6551.1	6289.0
6	115	0.96	200.0	194.1	5.9	200.0	188.2	11.8	115.0	146.1	117.3	117.3	114.2	117.2	4206.4	4082.4	2344.6	2206.6	6551.1	6289.0
7	115	0.96	200.0	193.5	6.5	200.0	189.2	10.8	115.0	146.1	117.6	117.6	113.6	117.4	4206.4	4070.5	2344.6	2218.5	6551.1	6289.0
8	115	0.96	200.0	193.1	6.9	200.0	190.1	9.9	115.0	146.1	117.8	117.8	113.1	117.5	4206.4	4060.5	2344.6	2228.6	6551.1	6289.0
9	115	0.96	200.0	192.7	7.3	200.0	190.8	9.2	115.0	146.1	117.9	117.9	112.6	117.7	4206.4	4051.9	2344.6	2237.1	6551.1	6289.0
10	115	0.96	200.0	192.3	7.7	200.0	191.5	8.5	115.0	146.1	118.1	118.1	112.2	117.8	4206.4	4044.5	2344.6	2244.5	6551.1	6289.0
11	115	0.96	200.0	192.0	8.0	200.0	192.0	8.0	115.0	146.1	118.2	118.2	111.9	117.9	4206.4	4038.1	2344.6	2250.9	6551.1	6289.0
12	115	0.96	200.0	191.7	8.3	200.0	192.5	7.5	115.0	146.1	118.3	118.3	111.5	118.1	4206.4	4031.9	2344.6	2257.1	6551.1	6289.0
13	115	0.96	200.0	191.4	8.6	200.0	193.1	6.9	115.0	146.1	118.4	118.4	111.1	118.2	4206.4	4025.1	2344.6	2263.9	6551.1	6289.0
14	115	0.96	200.0	191.0	9.0	200.0	193.7	6.3	115.0	146.1	118.6	118.6	110.7	118.3	4206.4	4017.9	2344.6	2271.1	6551.1	6289.0
15	115	0.96	200.0	190.7	9.3	200.0	194.4	5.6	115.0	146.1	118.7	118.7	110.3	118.5	4206.4	4010.0	2344.6	2279.0	6551.1	6289.0
16	115	0.96	200.0	190.3	9.7	200.0	195.1	4.9	115.0	146.1	118.9	118.9	109.8	118.7	4206.4	4001.6	2344.6	2287.5	6551.1	6289.0
17	115	0.96	200.0	189.8	10.2	200.0	195.9	4.1	115.0	146.1	119.1	119.1	109.2	118.9	4206.4	3992.2	2344.6	2296.8	6551.1	6289.0
18	115	0.96	200.0	189.3	10.7	200.0	196.8	3.2	115.0	146.1	119.3	119.3	108.5	119.1	4206.4	3982.0	2344.6	2307.0	6551.1	6289.0
19	115	0.96	200.0	188.8	11.2	200.0	197.8	2.2	115.0	146.1	119.5	119.5	107.8	119.3	4206.4	3970.7	2344.6	2318.3	6551.1	6289.0
20	115	0.96	200.0	188.2	11.8	200.0	198.8	1.2	115.0	146.1	119.7	119.7	107.0	119.6	4206.4	3958.2	2344.6	2330.8	6551.1	6289.0
21	115	0.96	200.0	187.5	12.5	200.0	200.0	0.0	115.0	146.1	120.0	120.0	106.1	120.0	4206.4	3944.5	2344.6	2344.5	6551.1	6289.0

1 TDG saturation in Lake Roosevelt (%).
2 Power Generation Ratio = Power Output / Capacity Power Output.
3 Total Columbia River Flow (kcfs).
4 Total Powerhouse Flow (kcfs).
5 Total Spill Discharge (kcfs), outlet works discharge at Grand Coulee Dam.
6 TDG saturation of powerhouse discharge, assumed to equal the TDG saturation in the forebay (%).
7 TDG saturation in undiluted spill discharge (%).
8 Average TDG saturation in the Columbia River (%).
9 Capacity Power Output (MWhrs).
10 Power output (MWhrs).

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Table 2. Project Operations, Power, and TDG Production at Grand Coulee and Chief Joseph Dams (Case 1 Outlet Work flow, fbe=1256 ft)

	Grand Coulee		Chief Joseph	
Parameter	Case 1	Case 2	Case 1	Case 2
$Q_{total\ (kcfs)}$	200	200	200	200
$Q_{ph\ (kcfs)}$	180	200	167	130.1
$Q_{spill\ (kcfs)}$	20	0	33	68.9
MW_{hrs}	3786	4206	1958	1537
$TDG_{fb\ (\%)}$	125	125	130.4	125
$TDG_{sp\ (\%)}$	146.1	na	123.7	131.4
$TDG_{avg\ (\%)}$	130.4	125	129.3	127.2

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Table 3. Optimal Joint Project Operations and TDG Saturation at Grand Coulee (GCL) and Chief Joseph (CHJ) Dams (Power Generation Ratio = 0.90)

Input Parameters			Optimal Operations						TDG Saturation						Power Production					
			GCL			CHJ			GCL			CHJ			GCL		CHJ		Total	
Case	TDG_{fb} GCL	PGR	Q_{total}	Q_{ph}	Q_{sp}	Q_{total}	Q_{ph}	Q_{sp}	TDG_{ph}	TDGow	TDGavg	TDG_{ph}	TDG_{sp}	TDG_{avg}	MW_{max}	MW	MW_{max}	MW	MW_{Cap}	MW
1081	105.0	0.9	150.0	150.0	0.0	150.0	108.1	41.9	105.0	146.1	105.0	105.0	124.7	110.5	3213.7	3213.7	1793.7	1292.9	5007.3	4506.6
1082	105.0	0.9	160.0	160.0	0.0	160.0	115.3	44.7	105.0	146.1	105.0	105.0	125.7	110.8	3416.0	3416.0	1905.7	1373.5	5321.7	4789.5
1083	105.0	0.9	170.0	170.0	0.0	170.0	122.5	47.5	105.0	146.1	105.0	105.0	126.7	111.1	3616.5	3616.5	2016.8	1453.5	5633.3	5070.0
1084	105.0	0.9	180.0	180.0	0.0	180.0	129.7	50.3	105.0	146.1	105.0	105.0	127.6	111.3	3815.1	3815.1	2127.0	1532.8	5942.1	5347.9
1085	105.0	0.9	190.0	190.0	0.0	190.0	136.9	53.1	105.0	146.1	105.0	105.0	128.6	111.6	4011.8	4011.8	2236.3	1611.5	6248.1	5623.3
1086	105.0	0.9	200.0	200.0	0.0	200.0	144.1	55.9	105.0	146.1	105.0	105.0	129.4	111.8	4206.4	4206.4	2344.6	1689.5	6551.1	5896.0
1087	105.0	0.9	210.0	210.0	0.0	210.0	151.3	58.7	105.0	146.1	105.0	105.0	130.3	112.1	4399.0	4399.0	2452.0	1766.9	6851.0	6165.9
1088	105.0	0.9	220.0	220.0	0.0	220.0	158.5	61.5	105.0	146.1	105.0	105.0	131.1	112.3	4589.4	4589.4	2558.5	1843.7	7148.0	6433.2
1089	105.0	0.9	230.0	230.0	0.0	230.0	156.8	73.2	105.0	146.1	105.0	105.0	133.1	114.0	4777.7	4777.7	2548.3	1815.7	7325.9	6593.3
1090	105.0	0.9	240.0	240.0	0.0	240.0	155.0	85.0	105.0	146.1	105.0	105.0	134.7	115.5	4963.6	4963.6	2538.0	1787.8	7501.6	6751.4
1091	105.0	0.9	250.0	248.4	1.6	250.0	156.1	93.9	105.0	146.1	105.7	105.7	135.8	117.0	5147.2	5113.4	2527.8	1794.1	7674.9	6907.4
1092	105.0	0.9	260.0	250.0	10.0	260.0	153.2	106.8	105.0	146.1	109.1	109.1	137.0	120.5	5123.4	5123.4	2517.5	1753.5	7640.9	6876.8
1093	110.0	0.9	150.0	150.0	0.0	150.0	108.1	41.9	110.0	146.1	110.0	110.0	124.7	114.1	3213.7	3213.7	1793.7	1292.9	5007.3	4506.6
1094	110.0	0.9	160.0	160.0	0.0	160.0	115.3	44.7	110.0	146.1	110.0	110.0	125.7	114.4	3416.0	3416.0	1905.7	1373.5	5321.7	4789.5
1095	110.0	0.9	170.0	170.0	0.0	170.0	122.5	47.5	110.0	146.1	110.0	110.0	126.7	114.7	3616.5	3616.5	2016.8	1453.5	5633.3	5070.0
1096	110.0	0.9	180.0	180.0	0.0	180.0	129.7	50.3	110.0	146.1	110.0	110.0	127.6	114.9	3815.1	3815.1	2127.0	1532.8	5942.1	5347.9
1097	110.0	0.9	190.0	190.0	0.0	190.0	136.9	53.1	110.0	146.1	110.0	110.0	128.6	115.2	4011.8	4011.8	2236.3	1611.5	6248.1	5623.3
1098	110.0	0.9	200.0	200.0	0.0	200.0	144.1	55.9	110.0	146.1	110.0	110.0	129.4	115.4	4206.4	4206.4	2344.6	1689.5	6551.1	5896.0
1099	110.0	0.9	210.0	210.0	0.0	210.0	151.3	58.7	110.0	146.1	110.0	110.0	130.3	115.7	4399.0	4399.0	2452.0	1766.9	6851.0	6165.9
1100	110.0	0.9	220.0	220.0	0.0	220.0	158.5	61.5	110.0	146.1	110.0	110.0	131.1	115.9	4589.4	4589.4	2558.5	1843.7	7148.0	6433.2
1101	110.0	0.9	230.0	230.0	0.0	230.0	156.8	73.2	110.0	146.1	110.0	110.0	133.1	117.4	4777.7	4777.7	2548.3	1815.7	7325.9	6593.3
1102	110.0	0.9	240.0	240.0	0.0	240.0	155.0	85.0	110.0	146.1	110.0	110.0	134.7	118.8	4963.6	4963.6	2538.0	1787.8	7501.6	6751.4
1103	110.0	0.9	250.0	249.0	1.0	250.0	154.9	95.1	110.0	146.1	110.4	110.4	135.9	120.1	5147.2	5127.2	2527.8	1780.2	7674.9	6907.4
1104	110.0	0.9	260.0	250.0	10.0	260.0	153.2	106.8	110.0	146.1	113.6	113.6	137.0	123.2	5123.4	5123.4	2517.5	1753.5	7640.9	6876.8
1105	115.0	0.9	150.0	150.0	0.0	150.0	108.1	41.9	115.0	146.1	115.0	115.0	124.7	117.7	3213.7	3213.7	1793.7	1292.9	5007.3	4506.6
1106	115.0	0.9	160.0	160.0	0.0	160.0	115.3	44.7	115.0	146.1	115.0	115.0	125.7	118.0	3416.0	3416.0	1905.7	1373.5	5321.7	4789.5
1107	115.0	0.9	170.0	170.0	0.0	170.0	122.5	47.5	115.0	146.1	115.0	115.0	126.7	118.3	3616.5	3616.5	2016.8	1453.5	5633.3	5070.0

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Table 3. Optimal Joint Project Operations and TDG Saturation at Grand Coulee (GCL) and Chief Joseph (CHJ) Dams (Power Generation Ratio = 0.90)

Input Parameters			Optimal Operations						TDG Saturation						Power Production					
			GCL			CHJ			GCL			CHJ			GCL		CHJ		Total	
Case	TDG_{fb} GCL	PGR	Q_{total}	Q_{ph}	Q_{sp}	Q_{total}	Q_{ph}	Q_{sp}	TDG_{ph}	TDGow	TDGavg	TDG_{ph}	TDG_{sp}	TDG_{avg}	MW_{max}	MW	MW_{max}	MW	MW_{Cap}	MW
1108	115.0	0.9	180.0	180.0	0.0	180.0	129.7	50.3	115.0	146.1	115.0	115.0	127.6	118.5	3815.1	3815.1	2127.0	1532.8	5942.1	5347.9
1109	115.0	0.9	190.0	190.0	0.0	190.0	136.9	53.1	115.0	146.1	115.0	115.0	128.6	118.8	4011.8	4011.8	2236.3	1611.5	6248.1	5623.3
1110	115.0	0.9	200.0	200.0	0.0	200.0	144.1	55.9	115.0	146.1	115.0	115.0	129.4	119.0	4206.4	4206.4	2344.6	1689.5	6551.1	5896.0
1111	115.0	0.9	210.0	210.0	0.0	210.0	151.3	58.7	115.0	146.1	115.0	115.0	130.3	119.3	4399.0	4399.0	2452.0	1766.9	6851.0	6165.9
1112	115.0	0.9	220.0	220.0	0.0	220.0	158.5	61.5	115.0	146.1	115.0	115.0	131.1	119.5	4589.4	4589.4	2558.5	1843.7	7148.0	6433.2
1113	115.0	0.9	230.0	230.0	0.0	230.0	156.8	73.2	115.0	146.1	115.0	115.0	133.1	120.8	4777.7	4777.7	2548.3	1815.7	7325.9	6593.3
1114	115.0	0.9	240.0	240.0	0.0	240.0	155.0	85.0	115.0	146.1	115.0	115.0	134.7	122.0	4963.6	4963.6	2538.0	1787.8	7501.6	6751.4
1115	115.0	0.9	250.0	249.9	0.1	250.0	153.3	96.7	115.0	146.1	115.0	115.0	136.0	123.1	5147.2	5146.1	2527.8	1761.4	7674.9	6907.4
1116	115.0	0.9	260.0	250.0	10.0	260.0	153.2	106.8	115.0	146.1	118.1	118.1	137.0	125.9	5123.4	5123.4	2517.5	1753.5	7640.9	6876.8
1117	120.0	0.9	150.0	150.0	0.0	150.0	108.1	41.9	120.0	146.1	120.0	120.0	124.7	121.3	3213.7	3213.7	1793.7	1292.9	5007.3	4506.6
1118	120.0	0.9	160.0	160.0	0.0	160.0	115.3	44.7	120.0	146.1	120.0	120.0	125.7	121.6	3416.0	3416.0	1905.7	1373.5	5321.7	4789.5
1119	120.0	0.9	170.0	170.0	0.0	170.0	122.5	47.5	120.0	146.1	120.0	120.0	126.7	121.9	3616.5	3616.5	2016.8	1453.5	5633.3	5070.0
1120	120.0	0.9	180.0	180.0	0.0	180.0	129.7	50.3	120.0	146.1	120.0	120.0	127.6	122.1	3815.1	3815.1	2127.0	1532.8	5942.1	5347.9
1121	120.0	0.9	190.0	190.0	0.0	190.0	136.9	53.1	120.0	146.1	120.0	120.0	128.6	122.4	4011.8	4011.8	2236.3	1611.5	6248.1	5623.3
1122	120.0	0.9	200.0	200.0	0.0	200.0	144.1	55.9	120.0	146.1	120.0	120.0	129.4	122.6	4206.4	4206.4	2344.6	1689.5	6551.1	5896.0
1123	120.0	0.9	210.0	210.0	0.0	210.0	151.3	58.7	120.0	146.1	120.0	120.0	130.3	122.9	4399.0	4399.0	2452.0	1766.9	6851.0	6165.9
1124	120.0	0.9	220.0	220.0	0.0	220.0	158.5	61.5	120.0	146.1	120.0	120.0	131.1	123.1	4589.4	4589.4	2558.5	1843.7	7148.0	6433.2
1125	120.0	0.9	230.0	230.0	0.0	230.0	156.8	73.2	120.0	146.1	120.0	120.0	133.1	124.2	4777.7	4777.7	2548.3	1815.7	7325.9	6593.3
1126	120.0	0.9	240.0	240.0	0.0	240.0	155.0	85.0	120.0	146.1	120.0	120.0	134.7	125.2	4963.6	4963.6	2538.0	1787.8	7501.6	6751.4
1127	120.0	0.9	250.0	250.0	0.0	250.0	153.2	96.8	120.0	146.1	120.0	120.0	136.0	126.2	5147.2	5147.2	2527.8	1760.3	7674.9	6907.4
1128	120.0	0.9	260.0	250.0	10.0	260.0	153.2	106.8	120.0	146.1	122.6	122.6	137.0	128.5	5123.4	5123.4	2517.5	1753.5	7640.9	6876.8
1129	125.0	0.9	150.0	150.0	0.0	150.0	108.1	41.9	125.0	146.1	125.0	125.0	124.7	124.9	3213.7	3213.7	1793.7	1292.9	5007.3	4506.6
1130	125.0	0.9	160.0	160.0	0.0	160.0	115.3	44.7	125.0	146.1	125.0	125.0	125.7	125.2	3416.0	3416.0	1905.7	1373.5	5321.7	4789.5
1131	125.0	0.9	170.0	170.0	0.0	170.0	122.5	47.5	125.0	146.1	125.0	125.0	126.7	125.5	3616.5	3616.5	2016.8	1453.5	5633.3	5070.0
1132	125.0	0.9	180.0	180.0	0.0	180.0	129.7	50.3	125.0	146.1	125.0	125.0	127.6	125.7	3815.1	3815.1	2127.0	1532.8	5942.1	5347.9
1133	125.0	0.9	190.0	190.0	0.0	190.0	136.9	53.1	125.0	146.1	125.0	125.0	128.6	126.0	4011.8	4011.8	2236.3	1611.5	6248.1	5623.3
1134	125.0	0.9	200.0	200.0	0.0	200.0	144.1	55.9	125.0	146.1	125.0	125.0	129.4	126.2	4206.4	4206.4	2344.6	1689.5	6551.1	5896.0
1135	125.0	0.9	210.0	210.0	0.0	210.0	151.3	58.7	125.0	146.1	125.0	125.0	130.3	126.5	4399.0	4399.0	2452.0	1766.9	6851.0	6165.9

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Table 3. Optimal Joint Project Operations and TDG Saturation at Grand Coulee (GCL) and Chief Joseph (CHJ) Dams (Power Generation Ratio = 0.90)

Input Parameters			Optimal Operations						TDG Saturation						Power Production					
			GCL			CHJ			GCL			CHJ			GCL		CHJ		Total	
Case	TDG_{fb} GCL	PGR	Q_{total}	Q_{ph}	Q_{sp}	Q_{total}	Q_{ph}	Q_{sp}	TDG_{ph}	TDGow	TDGavg	TDG_{ph}	TDG_{sp}	TDG_{avg}	MW_{max}	MW	MW_{max}	MW	MW_{Cap}	MW
1136	125.0	0.9	220.0	220.0	0.0	220.0	158.5	61.5	125.0	146.1	125.0	125.0	131.1	126.7	4589.4	4589.4	2558.5	1843.7	7148.0	6433.2
1137	125.0	0.9	230.0	230.0	0.0	230.0	156.8	73.2	125.0	146.1	125.0	125.0	133.1	127.6	4777.7	4777.7	2548.3	1815.7	7325.9	6593.3
1138	125.0	0.9	240.0	240.0	0.0	240.0	155.0	85.0	125.0	146.1	125.0	125.0	134.7	128.4	4963.6	4963.6	2538.0	1787.8	7501.6	6751.4
1139	125.0	0.9	250.0	250.0	0.0	250.0	153.2	96.8	125.0	146.1	125.0	125.0	136.0	129.3	5147.2	5147.2	2527.8	1760.3	7674.9	6907.4
1140	125.0	0.9	260.0	250.0	10.0	260.0	153.2	106.8	125.0	146.1	127.1	127.1	137.0	131.2	5123.4	5123.4	2517.5	1753.5	7640.9	6876.8
1141	130.0	0.9	150.0	150.0	0.0	150.0	108.1	41.9	130.0	146.1	130.0	130.0	124.7	128.5	3213.7	3213.7	1793.7	1292.9	5007.3	4506.6
1142	130.0	0.9	160.0	160.0	0.0	160.0	115.3	44.7	130.0	146.1	130.0	130.0	125.7	128.8	3416.0	3416.0	1905.7	1373.5	5321.7	4789.5
1143	130.0	0.9	170.0	170.0	0.0	170.0	122.5	47.5	130.0	146.1	130.0	130.0	126.7	129.1	3616.5	3616.5	2016.8	1453.5	5633.3	5070.0
1144	130.0	0.9	180.0	180.0	0.0	180.0	129.7	50.3	130.0	146.1	130.0	130.0	127.6	129.3	3815.1	3815.1	2127.0	1532.8	5942.1	5347.9
1145	130.0	0.9	190.0	190.0	0.0	190.0	136.9	53.1	130.0	146.1	130.0	130.0	128.6	129.6	4011.8	4011.8	2236.3	1611.5	6248.1	5623.3
1146	130.0	0.9	200.0	200.0	0.0	200.0	144.1	55.9	130.0	146.1	130.0	130.0	129.4	129.8	4206.4	4206.4	2344.6	1689.5	6551.1	5896.0
1147	130.0	0.9	210.0	210.0	0.0	210.0	151.3	58.7	130.0	146.1	130.0	130.0	130.3	130.1	4399.0	4399.0	2452.0	1766.9	6851.0	6165.9
1148	130.0	0.9	220.0	220.0	0.0	220.0	158.5	61.5	130.0	146.1	130.0	130.0	131.1	130.3	4589.4	4589.4	2558.5	1843.7	7148.0	6433.2
1149	130.0	0.9	230.0	230.0	0.0	230.0	156.8	73.2	130.0	146.1	130.0	130.0	133.1	131.0	4777.7	4777.7	2548.3	1815.7	7325.9	6593.3
1150	130.0	0.9	240.0	240.0	0.0	240.0	155.0	85.0	130.0	146.1	130.0	130.0	134.7	131.7	4963.6	4963.6	2538.0	1787.8	7501.6	6751.4
1151	130.0	0.9	250.0	250.0	0.0	250.0	153.2	96.8	130.0	146.1	130.0	130.0	136.0	132.3	5147.2	5147.2	2527.8	1760.3	7674.9	6907.4

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Table 4. Spill Distribution between Chief Joseph and Grand Coulee Dams.		
Event	Spill Discharge (kcfs)	
	CHJ	GCL*
1	20	0
2	40	0
3	60	0
4	70	0
5	80	4
6	90	8
7	100	12
8	110	16

* Outlet works flow at Grand Coulee Dam

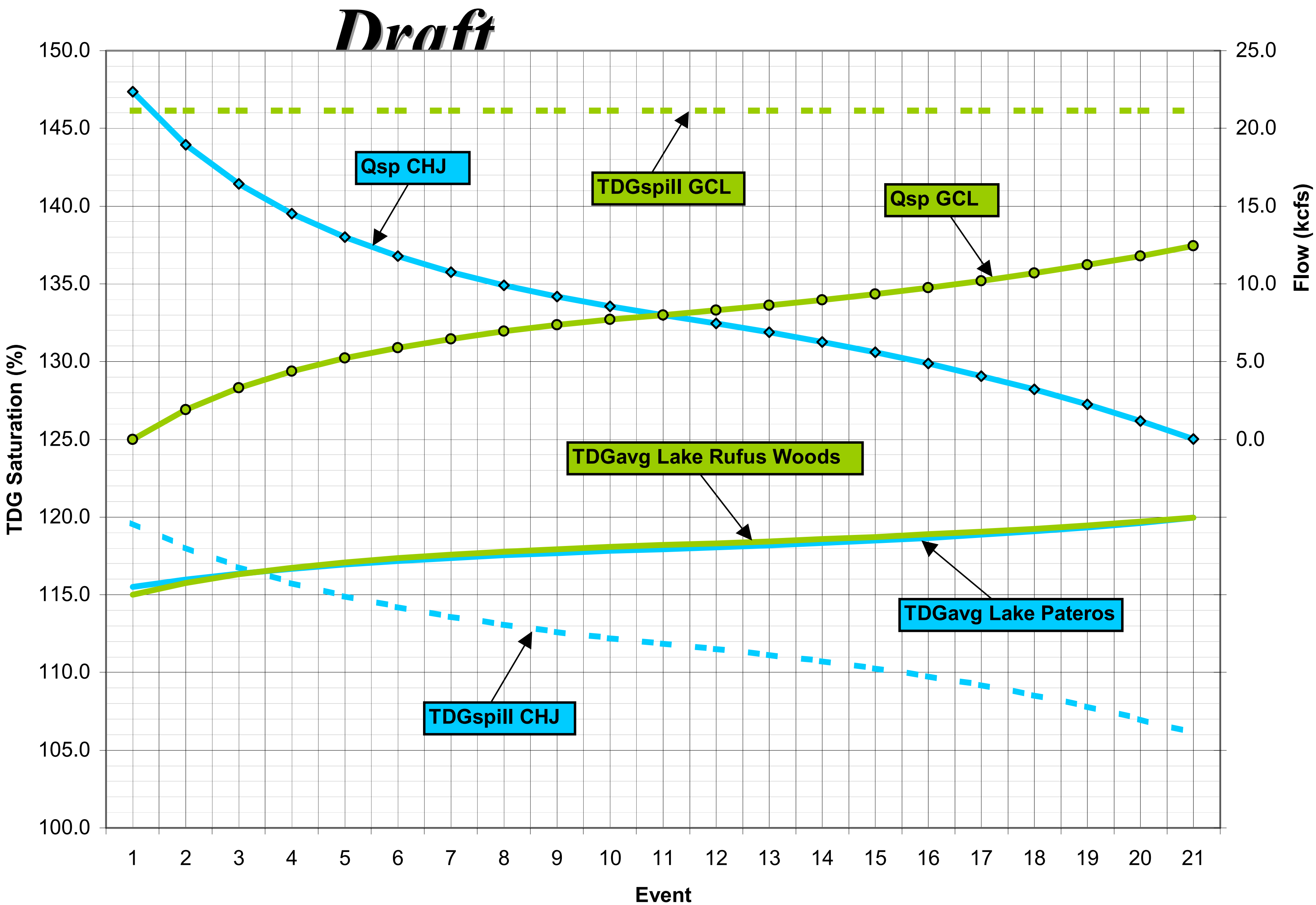

Figure 1. Joint Project Operations at Chief Joseph and Grand Coulee Dams and TDG Saturation in the Columbia River for a Constant Joint Power Output of 6289 MW_{hrs}.

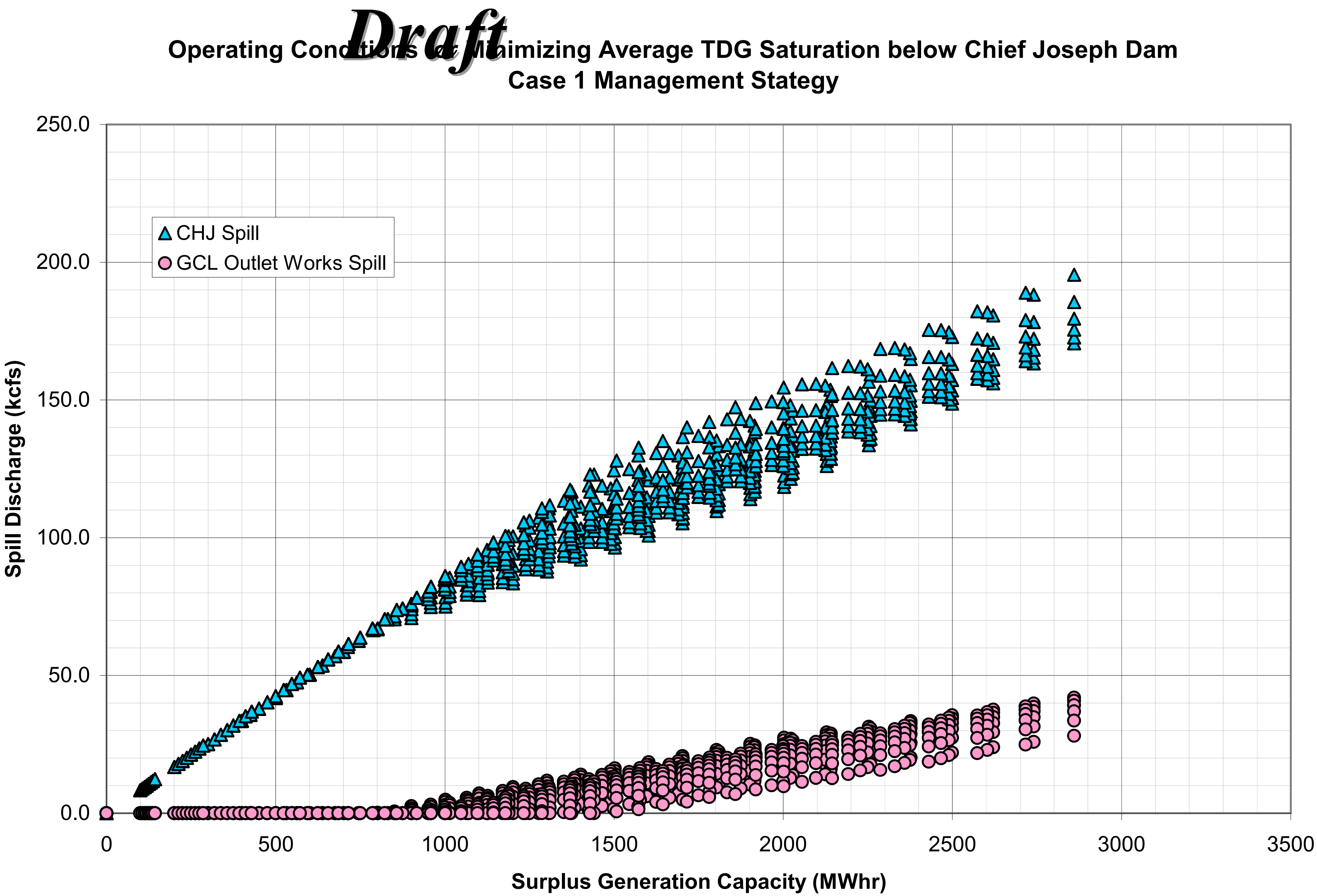

Figure 2. Optimal Joint Spill Discharge as a Function of the Surplus Generation Capacity for Chief Joseph and Grand Coulee Dams, (TDG Objective was to minimize the average TDG saturation below Chief Joseph Dam)

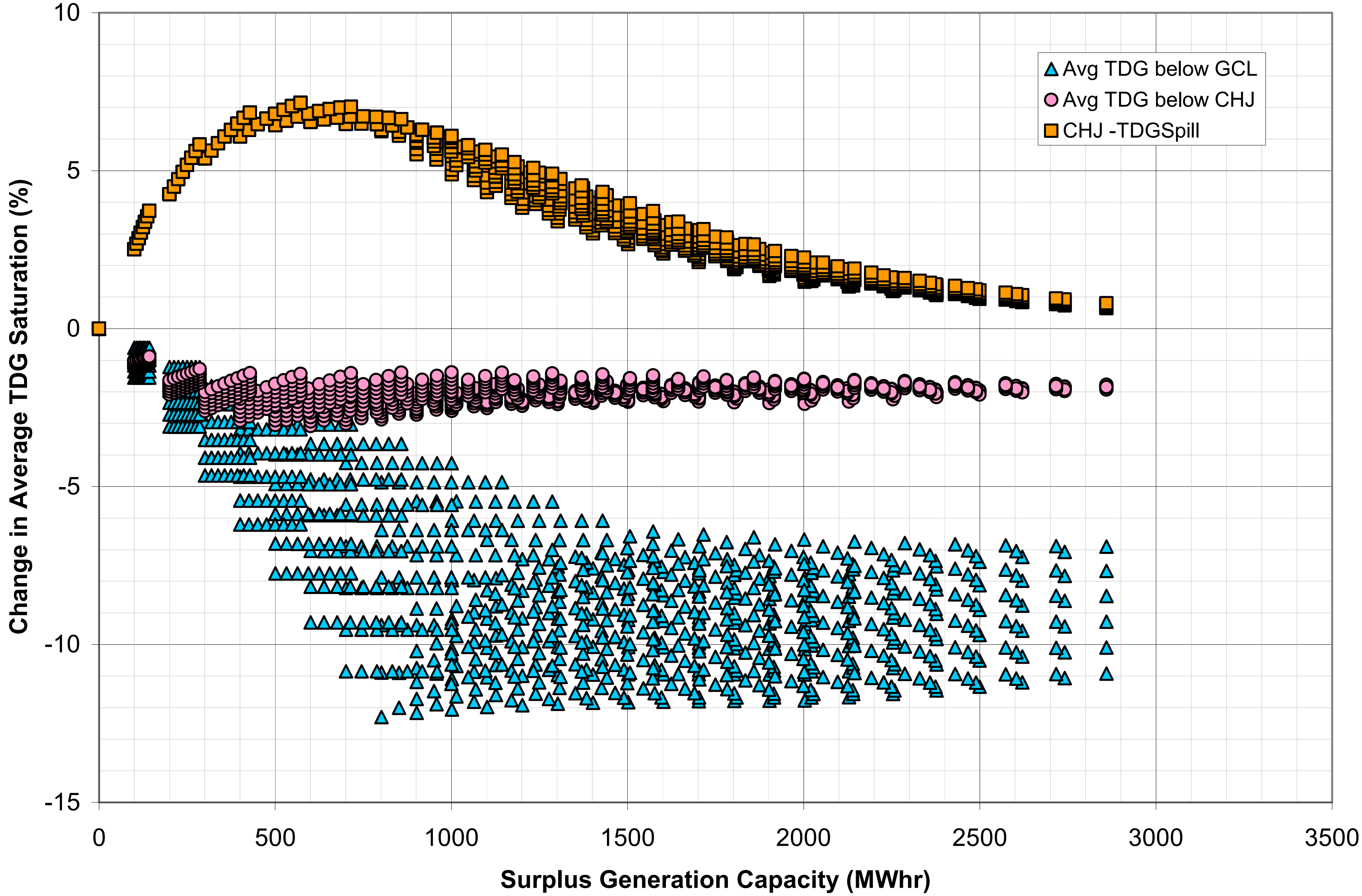

Figure 3. Change in TDG Saturation for Base and Optimal Operating Conditions for Chief Joseph and Grand Coulee Dams, (Negative/Positive Chainge in TDG Saturation indicates reduction/increase in TDG Saturation caused by optimal operations)

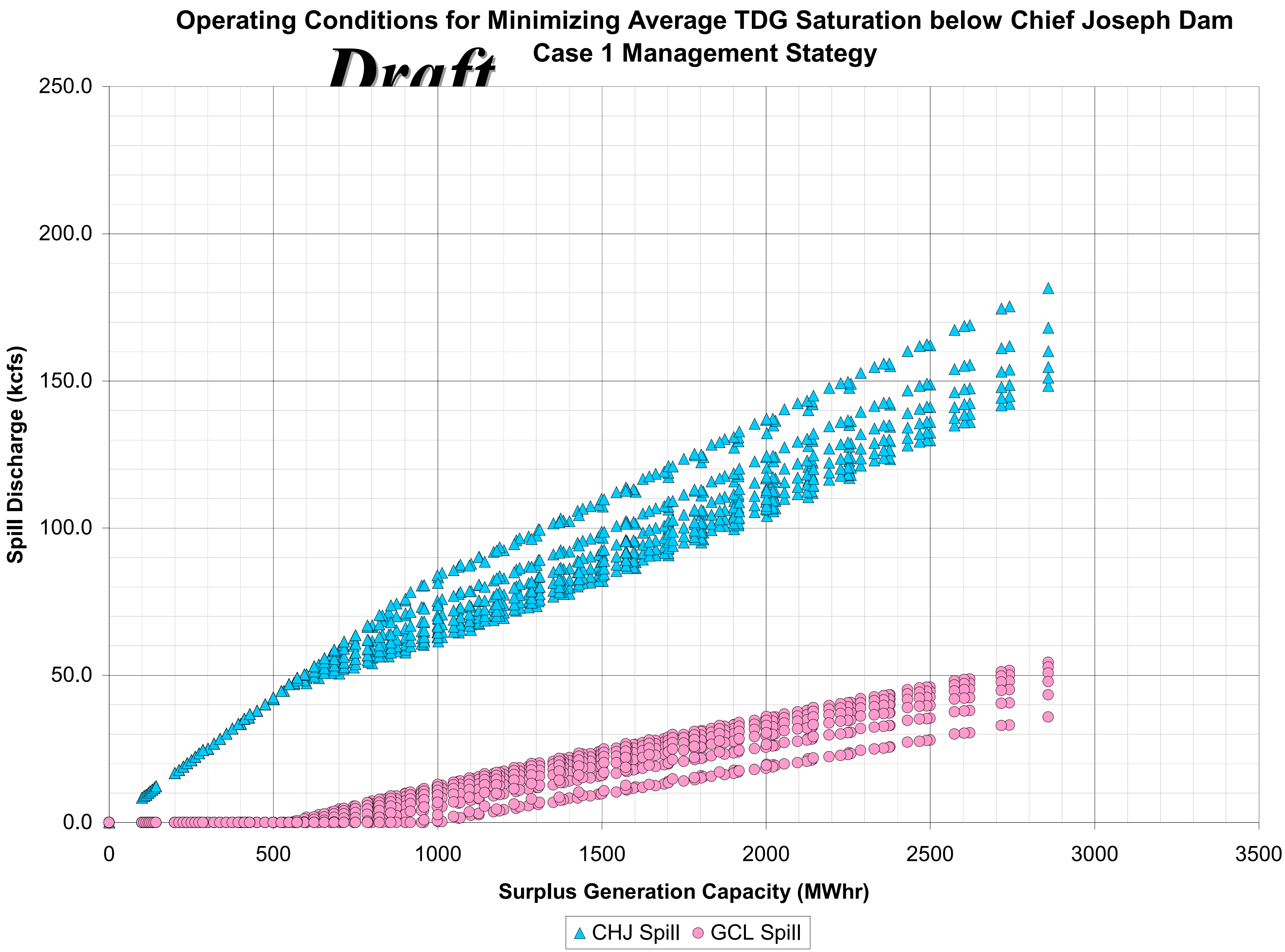

Figure 4. Optimal Joint Spill Discharge as a Function of the Surplus Generation Capacity for Chief Joseph and Grand Coulee Dams, (TDG Objective was to minimize the average TDG saturation below Chief Joseph Dam, 25% reduction in outlet work TDG loading at GCL)